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Explanatory analysis of the relationship between atmospheric circulation and occurrence of flood generating events in a coastal city

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Abstract

The aim of this study is to enhance the understanding of the occurrence of flood generating events in urban areas by analyzing the relationship between large-scale atmospheric circulation and extreme precipitation events, extreme sea water level events and their simultaneous occurrence, respectively. To describe the atmospheric circulation we used the Lamb circulation type (LCT) classification and re-grouped it into Lamb circulation classes (LCC). The daily LCCs/LCTs were connected with rare precipitation and water level events in Aarhus, a Danish coastal city. Westerly and cyclonic LCCs (*W*, *C*, *SW*, and *NW*) showed a significantly high occurrence of extreme precipitation. Similarly, for extreme water level events westerly LCCs (*W* and *SW*) showed a significantly high occurrence. Significantly low occurrence of extreme precipitation and water level events was obtained in easterly LCCs (*NE*, *E*, and *SE)*. For concurrent events significantly high occurrence was obtained in LCC *W*. We assessed the change in LCC occurrence frequency in the future based on two regional climate models (RCMs). The projections indicate that the westerly directions in LCCs are expected to increase in the future. Consequently, simultaneous occurrence of extreme water level and precipitation events is expected to increase in the future as a result of change in LCC frequencies. The RCM projections for LCC frequencies are uncertain because the representation of current LCCs is poor; a large number of days cannot be classified and the frequencies of the days that can be classified differ from the observed time series.

Key words: Atmospheric circulation, Lamb circulation type classification, flood hazards, extreme precipitation, extreme water levels, concurrent events, regional climate models

1 Introduction

Over the last few decades Europe has experienced an increasing number of damaging floods caused by different flood hazards such as extreme precipitation (Gregersen *et al.*, 2014; Willems, 2013) and high sea water levels (Hallegatte *et al.*, 2013). With anticipated climate change an increase in the occurrence and magnitude of flood generating events is expected (Arnbjerg-Nielsen, 2012; Sunyer *et al.*, 2015). These expected climate change impacts are exacerbated by an increasing concentration of assets in urban areas, leading to further flood damage (SwissRe, 2012). Flood risk management practices focus on adapting cities to flooding in an effort to minimizing expected annual damage (Zhou *et al.*, 2012; Zevenbergen *et al.*, 2008). Our capability to prepare and adapt to the increase in flood damages is, however, challenged by large uncertainties and knowledge gaps that are associated with flood generating events (Apel *et al.*, 2004). To improve our understanding of causes for flooding we need to develop means to describe drivers of flood generating events, such as large-scale atmospheric circulation.

It is known that large-scale atmospheric circulation influences local and regional climate (Kidson, 1994) and is considered an important factor when aiming at improving our understanding of local weather conditions and the occurrence of extreme events (Post *et al.,* 2002; Stehlik & Bárdossy 2002; Garavaglia *et al.,* 2010). To describe atmospheric circulation patterns, different circulation type classifications (CTCs) are commonly used. A large number of classifications are available today. For example, the COST Action 733 (Harmonization and applications of weather type classifications for European regions) reviewed 72 classifications (Philipp *et al.,* 2010) for Europe. CTCs classify circulation states into distinct groups (Philipp *et al.,* 2010) and are considered an important tool for analyzing a range of weather and climate conditions (Philipp *et al.,* 2010; Jacobeit, 2010). They compress information into catalogs and become useful in applications for achieving clearly structured results from complex data sets (Jacobeit, 2010). On the other hand, the compression may lead to loss of information, which leads to difficulties in relating the remaining information to the studied weather phenomena (Philipp *et al.,* 2010). Consequently, there exists no generally accepted classification system, as CTCs are purpose-made simplifications rather than a physical reality (Huth *et al.,* 2008). In relation to this, Lupikasza (2010) analysed three different CTCs developed in Poland with common circulation types (CTs). She found a low agreement between the different classifications, as only 7.9% of the days had the same CT. Schiemann *et al.* (2009) made an extensive study assessing the ability of CTCs to resolve daily precipitation in the Alpine region by using all CTCs reviewed in the COST Action 733 project. They concluded that, while there was a large variation in the predictive skill of the analysed CTCs, no "best" classification could be identified when taking sampling uncertainty into account. Hence, when utilizing CTCs in applications the suitability of the chosen classification needs to be considered.

The Lamb circulation type (LCT) classification, first developed by Lamb (1950) and later automated by Jenkinson *et al.* (1977) indicates flow direction and vorticity, and, hence, describes the prevailing pressure characteristic and presence of storms (Jenkinson *et al.*, 1977; Jones *et al.*, 1993; Jones, 2013). Several studies focusing on the relationship between large-scale atmospheric circulation and precipitation extremes have used the LCT classification; Trigo *et al.* (2000) in Portugal, Linderson (2001) in Sweden, Post *et al.* (2002) in Estonia, Fernández-González *et al.* (2012) in Spain and Jones *et al.* (2014) in UK. Additionally, analyses on the relationship between river discharge and LCTs have been conducted (Longfield & Macklin , 1999; Pattison & Lane, 2012). In the study by Schiemann *et al.* (2009) the LCT classification showed an average predictive skill for precipitation. This result, together with the large number of previous successful studies applying LCTs for assessing precipitation/discharge, justifies choosing the LCT classification scheme for studying atmospheric circulation likely to describe flood generating events. Reanalysis products, which have recently become available, have enabled automated LCT calculation techniques to be applied to consistently produced surface pressure data (Jones *et al.*, 2013). Hence, in this study we utilize the ERA-40 re-analysis meteorological data (Betts *et al.*, 2003) to develop daily LCTs.

The objective of this study is to contribute to an enhanced understanding of the occurrence of flood generating events with an analysis of the relationship between occurrence of flood generating events and large-scale atmospheric circulation by means of LCTs. We focus our analyses on events caused by precipitation and sea water levels in a coastal city including consideration of their simultaneous occurrence. The objective of this study is threefold.

Firstly, our objective is to assess the relationship between LCTs and high precipitation/sea water level events, respectively. Most studies focusing on relationship between precipitation and CTs have used a daily temporal resolution (Post *et al.*, 2002; Trigo *et al.*, 2000). This is, however, too coarse when analysing flood generating precipitation events at an urban scale where catchments are smaller and runoff concentration times are shorter than one day. This study contributes to the research on the relationship between LCTs and precipitation events by selecting the maximum intensity observed over 3 hours during each day, corresponding to the concentration time of a large urban catchment and hence the measure that will provide the maximum impact on the catchment. Additionally, to our knowledge, no studies have assessed the relationship between high sea water levels and large-scale atmospheric circulation by means of LCTs. High sea water levels around Denmark are a result of a passage of a low pressure centre, with strong winds from specific directions, depending on the direction the coast is facing and on its openness to the sea. The build-up of high sea water levels may need a longer time period of particular wind direction. We consider this by assessing the relationship between high sea water level events and LCTs on the same day and the preceding day.

Secondly, we examine the relationship between LCTs and high precipitation/sea water level events in the context of their simultaneous occurrence. Concurrent occurrences of precipitation and sea water level events are often ignored in flood risk studies, perhaps because they most frequently occur in different seasons (Pedersen *et al.,* 2012). When such simultaneous events do occur, flood damage may be notably larger than otherwise. With the anticipated increase in the occurrence of floods, there is a need to establish means to describe the occurrence of concurrent events in order to define to what extent such events will become more frequent in the future.

Thirdly, we analyze if regional climate model (RCM) data can be used to assess the occurrence frequency of high precipitation and sea water level events in the future by means of identifying frequency changes in LCTs. Previous studies have used global circulation model (GCM) data to analyze changes in LCTs (Demuzere *et al.*, 2009; Lorenzo *et al.*, 2011). Further, some studies have used observed LCTs to improve the downscaling of RCM precipitation data to local scales (Wetterhall *et al.*, 2012). According to our knowledge, no previous studies have analysed the usability of RCM data to directly describe LCT frequencies and their future changes. We assess the change in precipitation and sea water level events as a result of changes in LCT occurrence frequency derived from RCMs. Hence, we describe to what extent the change in LCT occurrence frequency alone may contribute to the increase in occurrence of flood generating events.

2 Methodology

2.1 Data sets

For our analysis we used Aarhus, a Danish coastal city, as a case study area. Precipitation data were provided by the Water Pollution Committee of The Society of Danish Engineers (SVK) for precipitation gauging station 5517 with data available from 1979. Water level data for Aarhus harbour were provided by the Danish Meteorological Institute. Both datasets are available in sub-hourly resolutions and have been sampled to maximum 3-hour precipitation intensity and maximum hourly sea level for each day, respectively. Hence, these measures are used as metrics of daily extremes rather than aggregated daily averages.

With regard to daily mean sea level pressure (MSLP), required to calculate LCTs, ERA-40 re-analysis meteorological data (spatial resolution T85, corresponding to 100 by 150 km), produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) were used (Betts *et al.*, 2003). Data were available during 1958-2001. Hence, due to limited data availability, the analysis in this study was conducted for the time period 1979-2001 (23 years).

Further, MSLP data from two RCM simulations carried out with the HIRHAM model as part of the ENSEMBLES project (van der Linden *et al.*, 2009), which utilized ERA-40 reanalysis data as boundary conditions in the control period, were used to calculate LCTs for the time periods 1961-1990 (control period) and 2070-2099 (future period). These RCMs (with spatial resolution 25 by 25 km) were 1) ECHAM/HIRHAM (forced by ECHAM global model simulations), and 2) BCM/HIRHAM (forced by BCM global model simulations).

2.2 Lamb circulation type classification

We computed the LCTs by means of six circulation indices (Jones *et al.,* 1993) and classification rules defined by Jenkinson *et al.* (1977). The 16 grid points, $p(n)$, used to extract MSLP (see Figure 1), have the centre located at 55°N, similar to Jones *et al.* (1993). The indices are calculated as (Jones *et al.*, 1993):

$$W = 0.5[p(12) + p(13) - p(4) - p(5)] \quad \text{(westerly flow)} \quad (1)$$

$$S = 1.74\left[\tfrac{1}{4}\big(p(5) + 2p(9) + p(13)\big) - \tfrac{1}{4}\big(p(4) + 2p(8) - p(2)\big)\right] \quad \text{(southerly flow)} \quad (2)$$

$$F = (S^2 + W^2)^{\frac{1}{2}} \quad \text{(resultant flow)} \quad (3)$$

$$ZW = 1.07[0.5(p(15) + p(16)) - 0.5(p(8) + p(9)] - 0.95[0.5(p(8) - p(9)) - 0.5(p(1) + p(2))] \quad \text{(westerly shear vorticity)} \tag{4}$$

$$ZS = 1.52[0.25(p(6) + 2p(10) + p(14)) - 0.25(p(5) + 2p(9) + p(13)) - 0.25(p(4) + 2p(8) + p(12) + 0.25(p(3) + 2p(7) + p(11))] \quad \text{(southerly shear vorticity)} \tag{5}$$

$$Z = ZW + ZS \quad \text{(total shear vorticity)} \tag{6}$$

W and *S* are westerly (zonal) and southerly (meridional) components of the geostrophic (surface) wind, and *F* is the combined wind speed. *ZW* and *ZS* are the westerly and southerly shear vorticity, and *Z* is the total vorticity. The following rules were identified by Jenkinson *et al.* (1977) to define automated LCTs from the indices:

1) The direction of flow is $\tan^{-1}$ (*W*/*S*). Add 180 ° if *W* is positive. The appropriate direction is calculated on an eight-point compass allowing 45° per sector. Thus *W* occurs between 247.5° and 292.5°
2) If |*Z*| >*F*, flow is essentially straight and corresponds to Lamb pure directional type
3) If |*Z*|>2*F*, then the type is strongly cyclonic (*Z*>0) or anticyclonic (*Z*<0). This corresponds to Lamb's pure cyclonic and anticyclonic types.
4) If *F*<|*Z*|<2*F*, then flow is partly cyclonic/anticyclonic and this corresponds to one of Lamb's hybrid types.
5) If *F* <6 and |*Z*|<6, the Lamb type is *U* (unknown)

The LCT classification has 26+1 classes subdivided into 8 directional types (*N, NE, E, SE, S, SW, W, NW*), 2 non-directional types (cyclonic *C* and anti-cyclonic *A*), 15 hybrid types (*CN, CNE, CE, CSE, CSW, CW, CNW, AN, ANE, AE, ASE, AS, ASW, AW, ANW*), and one unclassified type (*U*) (Jenkinson *et al.*, 1977), see Table 2 for explanation of the abreviations.

The LCT classification can also be re-grouped to decrease the number of CTs (Mayes *et al.*, 1991; Trigo & DaCamara, 2000; Svensson *et al.*, 2002; Schiemann & Frei, 2009; van den Besselaar *et al.*, 2010; Lorenzo *et al.*, 2011). The advantage of such a grouping is that it may help to clarify the analysis and to obtain reasonable results with fewer data (Trigo & DaCamara, 2000). On the other hand, such a grouping may lead to further loss of information of the actual large-scale circulation pattern (Schiemann & Frei, 2009; Jacobeit, 2010).

In this study we analysed the relationship between high precipitation and sea water levels using both the original LCT classification and a grouped LCTs classification suggested by Trigo & DaCamara (2000). They re-grouped the 26 LCTs into 10 Lamb circulation classes (LCCs) by including the hybrid types into the directional and non-directional types. Each of the 16 hybrid types was included to the corresponding directional and non-directional types with a weight of 0.5 (Trigo & DaCamara, 2000). For example LCT *CNW* was included as 0.5 in *C* and 0.5 in *NW*.

2.3 Extraction of extreme values

The partial duration series (PDS) method, also called the peak over threshold (POT) method, was used to extract precipitation and sea water level events for the analysis. Maximum daily 3 hourly precipitation events (mm/3h) and maximum daily water level events were extracted from the data sets and utilized in the assessment. A minimum of 24 hours between two events was applied to ensure that the events are independent. Thresholds corresponding to, respectively, 20, 5, and 1 event per year on average were applied to the precipitation and water level data series. For the extraction of extreme events the EVA Toolbox developed by DHI MIKE by DHI, 2013) was used.

Table 1 presents the POT thresholds for 20, 5 and 1 events per year. The choice of threshold, and hence sample size, for the extreme value analysis is a question of assuring a sufficient amount of events for the analysis, and to represent a range of high precipitation and water level events. Due to the relatively short observation period (i.e. 23 years), 20 events/year was used to provide a larger data set for a more robust analysis. Using 1 event/year on the other hand provided a more accurate description of relevant extreme events, but the drawback was the very few observations included in the analysis.

2.4 Significance of circulation types for generating extreme events

We tested for a significantly high or low occurrence of precipitation and water level events in each LCT. The LCC classification was similarly used in the analysis. Hence, we tested whether the LCC classification can provide an equally good assessment of statistically significant occurrence.

To assess the statistical significance of water level events based on the combination of CTs the same day and the previous day we solely used the LCC classification. This choice was made to ensure enough data for each combination of days for a satisfactory analysis. We combined the LCCs into pairs of $LCC_{same\ day}$ -$LCC_{previous\ day}$, resulting in a total of 10×10 = 100 possible combinations, and assigned each water level event a pair of $LCC_{same\ day}$-$LCC_{previous\ day}$.

We used a statistical test and formulated the null hypothesis as:

H_0: The relative number of extreme events in a given LC (Lamb circulation) corresponds to the frequency of that LC, i.e. $\frac{N_i}{N_{tot} f_i} = 1$

with the alternate hypothesis being:

H_1: The relative number of extreme events in a given LC does not correspond to the frequency of that LC, i.e. $\frac{N_i}{N_{tot} f_i} \neq 1$

where N_i is the number of extreme events in *LC i,* which is the LCT, LCC or $LCC_{same\ day}$-$LCC_{previous\ day}$ pair, N_{tot} is the total number of extreme events, and f_i is the frequency of LC i calculated as:

$$f_i = \frac{t_i}{t_{tot}} \tag{7}$$

where t_i is the number of days with LC i and t_{tot} is the total observation period.

We assume that the occurrence of extreme events follows a Poisson distribution as typically done in POT analyses (e.g. Madsen *et al.*, 2002). We tested the hypothesis H_0 by constructing acceptance intervals for the expected number of extreme events in LC i. We compared the observed number of extremes N_i for each LC i with the acceptance intervals to identify LC with statistically significant over- or underrepresentation of precipitation/water level events. The acceptance intervals are constructed based on the expected number of events $N_{tot}f_i$, and calculated as (Johnson, 2005):

$$\tfrac{1}{2}\chi^2\left(2N_{tot}f_i, \tfrac{\alpha}{2}\right) < N_i < \tfrac{1}{2}\chi^2\left(2N_{tot}f_i + 2, 1 - \tfrac{\alpha}{2}\right) \tag{8}$$

where χ^2 is the quantile function of the chi-squared distribution, and α is the significance level.

2.5 Assessment of future occurrence of extreme events through a change in circulation type/class frequency

We assessed the change in occurrence of precipitation and water level events in the future based on the change in frequency of LCCs. The aim was to determine to what extent changes in LCC frequencies contribute to changes in the occurrence of events in the future. In this assessment we, therefore, focused solely on the change in occurrence frequency of events (on an annual and seasonal basis), and disregarded the change in the magnitude of events.

For the assessment, the change in frequency of LCCs from the RCM simulations was used to define climate factors (CF_i) for each LCC i as:

$$CF_i = \frac{t_{i,fut,RCM}}{t_{i,cont,RCM}} \tag{9}$$

where $t_{i,fut,RCM}$ is the number of days with LCC i according to RCM data in future period, and $t_{i,cont,RCM}$ is similarly the number of days with LCC i in the control period. Hence, to estimate the future number of days with LCC i ($t_{i,fut}$), the CFs were multiplied with the observed number of days with LCC i (t_i):

$$t_{i,fut} = CF_i t_i \tag{10}$$

Due to the differences between the simulated and observed LCC distributions in the control period, i.e. $t_i \neq t_{i,cont,RCM}$, the resulting total number of days in the future period becomes different from the number of days in the considered period. Therefore, the future number of days with each LCC i ($t_{i,fut}$) needs to be normalized by dividing by the total number of future days ($t_{tot,fut}$) to get the future frequency of LCC i ($f_{i,fut}$):

$$f_{i,fut} = \frac{t_{i,fut}}{t_{tot,fut}} \tag{11}$$

An individual occurrence rate r_i was calculated for each LCC i as:

$$r_i = \frac{N_i}{t_i} \tag{13}$$

The future average annual number of extreme events ($\lambda_{i,fut}$) could be assessed as:

$$\lambda_{i,fut} = r_i f_{i,fut} \tag{14}$$

The total number of extreme events per year in the future (λ_{fut}) was therefore defined as:

$$\lambda_{fut} = \sum_{LCC_1}^{LCC_{10}} \lambda_{i,fut} \quad (15)$$

3 Results

3.1 Lamb circulation types and classes

Current LCT and LCC (shaded) occurrence frequencies (f_i) calculated using reanalysis data are presented in Table 2 for thresholds 20, 5, and 1 events/year, respectively. LCTs *A*, *W*, *C*, *SW*, and *NW* have an occurrence frequency larger than 5 % and these LCTs account in total for 57 % of all days in the studied period. The anticyclonic LCT (*A*) has distinctly the largest occurrence frequency, over 20%. 12 LCTs have a frequency less than 2%. The unclassified type (*U*) was not observed during the studied period. These results are in accordance with LCT frequencies assessed in previous studies for UK (Pattison *& Lane*., 2012; Longfield *et al.*, 1999) and Sweden (Chen, 2000). LCC *A* is similarly dominant with over 30 %, and LCCs *W* and *C* have very similar frequencies. All LCCs have an occurrence frequency larger than 2 %.

3.2 Extraction of precipitation and sea water level extremes

The monthly frequencies of precipitation and water level events in Aarhus are presented in Figure 2. With a threshold of 20 events/year precipitation events are relatively evenly distributed over the year. With a threshold of 1 event/year events are observed only during half of the year, May-October. Water level extremes are on the other hand mainly observed in months September-March. This indicates that the annual cycles for precipitation and water level events are very different and that the extreme events do not occur during the same season.

3.3 Occurrence of extreme events in Lamb circulation types

Figure 3 presents occurrence frequency of precipitation events in each LCT together with the overall frequency of LCTs and corresponding acceptance intervals for 5 events/year with significance level α=0.2. Figure 4 similarly presents the results for water level events. We chose the significance level, α=0.2 after testing several significance levels (0.2, 0.1, 0.02). Hence, we were able to establish that the 0.2 provided the most stable result, and, therefore, the best possibility to compare the different thresholds.

Extreme precipitation events occurred in 25 LCTs with threshold 20 events/year, 19 LCTs with 5 events/year, and 10 LCTs with 1 event/year. *E* was the only LCT with no precipitation events for any of the thresholds. Water level events occurred in 25 LCTs with threshold 20 events/year, 18 LCTs with threshold 5 events/year, and 12 LCTs with 1 event/year. LCTs *AE* and *CE* had no occurrence of water level extremes with any of the analysed thresholds.

For the threshold 1 event/year three LCTs (*C*=22%, *SW*=13% *CSW*=13%) accounted for 48% of all precipitation events. Similarly, three LCTs (*A*=13%, *W*=17%, *SW*=22%) accounted for 52 % of the total number of water level events. Consequently, the LCT *SW* had a high frequency of both water level and precipitation events.

Many of the LCTs that are associated with a high occurrence frequency of events also have a high overall frequency. The large occurrence of events in these LCTs can potentially be related to the high frequency of the LCTs and, therefore, these LCTs do not necessarily generate more precipitation/water level events than expected. To identify LCTs/LCCs with precipitation/water level event occurrence higher than expected, we assess significant occurrence as presented below.

3.4 Lamb weather types/classes with significant occurrence of events

Table 3 and Table 4, derived from Figure 3 and Figure 4, present LCTs and LCCs with high and low occurrence of precipitation and water level events for the thresholds 20 events, 5 events and 1 event per year. With regards to calculating the lower acceptance interval (see Equation 8), $N_{tot}f_i$ should be larger than 0.5 events/year, as otherwise there is more than 10% probability that no extremes will be observed and, hence, no observations are acceptable. With thresholds 1 event/year, 14 LCTs do not meet this criterion, whereas all LCC have a large enough $N_{tot}f_i$ to allow for calculating the lower acceptance interval. Hence, with lower thresholds the LCC scheme is preferable.

Threshold 20 events/year provided a more extensive description of statistical significance than higher thresholds (5 evens and 1 event/ year) due to a larger sample size. While higher thresholds (5 events and 1 event/year) do not show significant occurrence to the same extent as the threshold 20 events/year, the assessment of higher/lower occurrence than expected (but not significant) is utilized to determine whether the results are consistent over different thresholds.

Very similar results were obtained for the LCT and LCC classifications. For the purpose of our study it appears that the LCCs provides a more suitable classification because it provides a similarly good assessment as the LCT classification and fewer types make the classification and the analysis clearer. The assessment is described in detail below.

3.4.1 Significant occurrence of precipitation events

For threshold 20 events/year, significantly low occurrence of precipitation was obtained in the LCTs and LCCs *A, NE, N, E*, and *SE*. Further, hybrid LCTs *AN, ANE, ASE* and *AE* obtained significantly low occurrence. Significantly high occurrence was obtained in LCTs and LCCs *W, C, SW*, and *NW*. In addition, hybrid LCT *CW* showed significantly high occurrence.

All LCCs that obtained significantly high occurrence with the threshold 20 events/year also obtained a higher than expected occurrence with 5 and 1 events/year. Hence, for high occurrence of precipitation events the LCC results are consistent over all thresholds. The LCT classification *W*, however, shows a low occurrence for the threshold 1 event/year in contrast to the other thresholds. Further, *N* obtained high occurrence with the threshold 1 event/year in both LCT and LCC classifications, in contrast to the thresholds 20 and 5 events per year.

3.4.2 Significant occurrence of water level events

For threshold 20 events/year, water level events obtained significantly low occurrence in LCTs and LCCs *C, NE, N, E*, and *SE*. LCT *N* obtained significantly low occurrence, while the same LCC obtained low but not significant occurrence. Further, hybrid LCTs *ANE, CSW, CNE, AS*, and *CE* showed statistically low significance. Significantly high occurrence was obtained for LCTs and LCCs *W* and *SW*. The hybrid LCT *AW* also showed significantly high occurrence.

With regards to consistency over different thresholds, LCT and LCC *A* showed high occurrence with thresholds 20 and 5 events/year, but for 1 event/year low occurrence was obtained. Further, *NW* obtained high, but not significant, occurrence for the threshold 20 events/year, but otherwise low, but not significant, occurrence for both the LCT and the LCC classification. Hence, these LCTs and LCCs are not consistent over the different thresholds, but the two classifications agree on the dissimilarities. For *S* the LCT and LCC classification do not agree for the thresholds 20 and 5 events/year; LCT obtained low occurrence and LCC obtained high occurrence. For the threshold 1 event/year both classifications show high occurrence for *S.*

Table 5 and Table 6 present low and high occurrence of water level events for a combination of LCCs the same day and the day before ($LCC_{same\ day}$ -$LCC_{previous\ day}$). For this assessment we used solely thresholds 20 events/year (Table 5) and 5 events/year (Table 6) to ensure a large enough data sample. For 20 events/year, significantly high occurrence was obtained in *W-W, W-NW, SW-SW, A-A* and *A-S*. All LCCs that contribute to significantly high occurrence of water level events also have a higher than expected occurrence in the assessment using only LCC for the same day with threshold 20 events/year (see Table 4). Significantly low occurrence of water level events was assessed for 21 $LCC_{same\ day}$-$LCC_{previous\ day}$ pairs. Further, we found that for threshold 20 events/year high occurrence was obtained for LCCs occurring two days in a row, i.e. if the same LCC occurs both the same day and the previous day. This could indicate that the build-up of high water level events require more than one day of similar circulation.

With threshold 5 events/year, significantly high occurrence was obtained for the pair *W-W*. Significantly low occurrence was obtained for 9 $LCC_{same\ day}$-$LCC_{previous\ day}$ pairs. All LCC pairs with significant occurrence for threshold 20 events/year showed similar high/low occurrence for the threshold 5 events/year. Hence, the results are consistent over these two thresholds.

3.4.3 Significant occurrence of concurrent events

When comparing Tables 3 and 4, we found that for threshold 20 events/year 7 out of 10 LCCs (i.e. *W, SW, NW, NE, N, E*, and *SE*) showed same over/underrepresentation of precipitation and water level events, corresponding to 51 % of the time. This result was not entirely consistent over the different thresholds. For threshold 5 events/year similar high/low occurrence was obtain for 6 out of 10 LCCs (*W, SW, NE, N, E, SE*) corresponding to 42 % of the time. For threshold 1 event/year the same high/low occurrence was obtained for 6 out of 10 LCCs (*A, W, SW, NE, E, SE*) corresponding to 67 % of the time. LCCs that obtained the same over-/underrepresentation of precipitation and water level events for all thresholds are *W, SW, NE, E,* and *SE* (corresponding to 36 % of the time).

For the assessment of concurrent events, precipitation and water level events were assumed to be concurrent if they occurred during the same day. The analysis was limited by the number of concurrent events found in the data set; for threshold 20 events/year only 1.3 concurrent events/year (in total 30 events) were observed. For the other two thresholds no concurrent events were observed. Seasonal occurrence frequency of concurrent events is presented in Figure 5. The highest frequency of concurrent events was observed in winter.

Figure 6 shows the occurrence frequency of concurrent events for each LCC for the threshold 20 events/year with corresponding acceptance intervals using significance level α=0.2 The LCCs *NE*, *N*, *E* and *SE* obtained no concurrent events. These LCCs also showed a significantly low occurrence of precipitation and water level events when looked at separately (described in Table 3 and 4). The LCC *W*, which had significantly high occurrence of both precipitation and water level events with threshold 20 events/year, obtained significantly high occurrence of concurrent events. Low occurrence of concurrent events was obtained in LCC *A*, which had high (but not significant) occurrence of water level events and a significantly low occurrence of precipitation events.

3.5 Assessment of future precipitation and water level events

We used the LCC classification to assess the occurrence of precipitation and water level events in the future. Figure 7 presents the LCC frequencies for BCM/HIRHAM and ECHAM/HIRHAM for the control period (1961-1990) together with the observed frequencies for the period 1979-2001. Although the control period from the RCMs is assumed to represent current conditions, there are substantial discrepancies between the observed LCCs and the LCCs calculated from the RCM outputs. The main difference is that for both models *C* has the highest frequency (*A* in the observed data) and that a high frequency of the unclassified type (*U*) is present in the RCM outputs.

Figure 8 presents the climate factors (CFs) for the total time period using BCM/HIRHAM and ECHAM/HIRHAM. In general, the changes between control and future periods are smaller than the errors in representing the current climate. Three LCCs show an increase in the future: *W*, *SW* and *NW*.

Figure 9 presents the future LCC frequencies based on Eq. (11) together with the frequency for the observed period. Three LCCs (*W, SW* and *NW*) show an increase in future frequencies. Table 7 presents the percent change in annual occurrence of water level, precipitation and concurrent events for the thresholds 20, 5 and 1 events/year as a result of the changes in LCC occurrence frequency between current and future time period. The two RCMs show an increase in the occurrence of water level events for all thresholds. Precipitation events also show an increase except for the threshold 1 event/year with ECHAM/HIRHAM. The highest increase was assessed for concurrent events according to both RCMs (15% and 19%).

Figure 10 presents future seasonal occurrence of extreme precipitation and water level events together with observed seasonal occurrence of extreme events. The results are relatively similar for both RCMs. Overall, it may be noted that the annual changes for precipitation and water level events are relatively equally distributed over the different seasons. Figure 11 presents the seasonal number of concurrent events. Both RCMs predict an increase of concurrent events in winter, spring, and autumn. BCM/HIRHAM shows a small decrease of concurrent events in summer.

4 Discussion

The LCT and LCC classifications were used to assess the relationship between large-scale atmospheric circulation and high precipitation/water level events. Due to limited data availability, we used a relatively short data set of observed precipitation and water level events (23 years). Therefore, we used a low threshold (20 events per year) to assess the dependence between atmospheric circulation patterns and probability of extremes to occur and verified the results by assessing the consistency with lower thresholds (5 events and 1 event per year). Given that the results are consistent across the different thresholds, it seems that the data set is sufficient to allow interpretation of the ability of atmospheric circulation patterns to predict weather extremes for our case study.

There are some limiting issues when using classifications for describing flood generating events. Firstly, in reality climatological variables do not follow a daily timescale and, therefore, daily LCTs might not be the most suitable representation of large-scale atmospheric circulation (Pattison & Lane, 2012). Daily LCTs are assessed using daily mean values for sea level pressure, and this may smoothen out possible fast changes in large-scale atmospheric circulation. Therefore, as we used 3 hourly precipitation and daily LCTs the results found in this study may be affected by the fact that the daily LCT does not reflect the LCT at the time of the analysed precipitation event. Moreover, the assessment on the relationship between water level events and LCTs indicated that perhaps the daily values do not reflect the entire build-up time of the high water level events. Consequently, daily LCTs may use a too long time interval of sea level pressure to describe precipitation events and a too short interval to describe water level events. The choice of a daily LCT is for our case study a necessary compromise in order to conduct the assessment for precipitation and water level events based on the same LCT data set and to allow for an analysis of concurrent events. To improve the description of the relationship between atmospheric circulation and precipitation/sea water level/concurrent events careful considerations of the temporal variations in climatological variables are needed.

Secondly, there may be regional differences in how well LCTs/LCCs can be related to flood generating events (Schiemann & Frei, 2009; Pattison & Lane, 2012). Regarding water level events, the occurrence depends on, for example, the direction that the analysed coast is facing and the openness to the sea. Aarhus is located on an eastern coast, and the build-up of high water levels at this location may require different atmospheric circulation than for locations on a western coast. Regional variations in precipitation events may, on the other hand, depend on the topography of the surrounding area.

Thirdly, Schiemann *et al.* (2009) showed that all the studied circulation classifications were better at predicting precipitation in winter and summer seasons in comparison with autumn and spring. The LCT/LCCs s capability to describe precipitation events may, therefore, have an annual variation. Our results, which are based on the relationships on an annual basis, may be affected by this annual variation. The issues related to describing relationships between precipitation events and LCTs/LCCs, i.e. the regional and seasonal variations, relate to the fact that LCTs/LCCs represent large-scale synoptic atmospheric processes and do not include details of the meso-scale convective systems (Schiemann & Frei, 2009), which often come with heavy rainstorms (Pattison & Lane, 2012). Hence, LCTs/LCCs alone are not able to provide an all-inclusive explanation of the occurrence of extreme precipitation events.

The analysis of the LCC occurrence frequency assessed from RCMs showed that the RCMs were relatively poor at reproducing observed LCCs. Numerous studies have used LCTs for a range of different assessments and hence we are surprised about the lack of ability to reproduce the LCT statistics of observed climate. In particular, the high occurrence of the unclassified weather type (U) raises some concern. It is, therefore, debatable whether RCM data used in this study may be adequate for describing future conditions. A reason for the increased occurrence of U could partly be the lack of interpolation of RCM data. Hence, the result of this study should be interpreted with caution and validated by other methods and simulations.

Using the RCM BCM/HIRHAM, a total of 59 % (396 days of 675) of all U days occurred in the summer season. For RCM ECHAM/HIRHAM, 38% (91 days of 240) of all U days occurred in the summer season. This result is in accordance with Grimalt *et al.* (2013), who also found a high occurrence of *U* days in the summer season in the Western Mediterranean Basin. In cases with high frequency of *U*, it could be more appropriate to utilize an automated Lamb classification that removes the *U* class from the catalogue attributing each *U* day to one of the other LCC classes, as for example described by Ramos *et al.* (2014).

To analyse the change in LCCs between current and future time we assumed that the control period from RCM data (1961-1990) can be compared with the data from the re-analysis product (1979-2001), and hence, we assume that the conditions are stationary under a time period of 40 years (1961-2001). Normally, stationarity is assumed for a time period of 20-30 years in climate studies. Therefore, our assumption is not ideal, but necessary due to the limited data availability, and it may weaken our conclusions. On the other hand, this study utilized the frequency change in RCM data to calculate climate factors for a description of future changes. This is a common approach in climate change analyses as the relative changes in RCM data generally are recognized as more reliable than absolute changes. Therefore, we consider the developed method a useful approach for evaluating the effect of changes in LCT frequencies on extreme weather events.

5 Conclusions

The probability of occurrence of extreme sea water levels as well as extreme precipitation is influenced by atmospheric circulation patterns. Using two classifications, we have identified patterns that give significantly higher and lower occurrence rates. These occurrences are persistent over a range of thresholds. The two classifications are the Lamb Classification Types (LCT) and Lamb Classification Class (LCC) of which the latter is a subset of 10 patterns of the 27 patterns defined using the original LCT.

We find that the LCC classification has three main advantages over the original LCT classification. Firstly, fewer classes make the classification and the analysis clearer. Secondly, due to the limited data set used in the analysis, the LCC classification could provide a better basis for obtaining statistical significance with higher thresholds. Thirdly, high and low occurrences (both significant and non-significant) were more consistent with the LCCs.

With a threshold of 20 events/year, LCCs *W, C, SW* and *NW* showed significantly high occurrence of 3 hourly maximum daily precipitation events, while significantly low occurrence was obtained in *A, NE, E* and *SE*. Water level events showed a significantly high occurrence in *W* and

SW. Significantly low occurrence was obtained in *C, NE, N, E*, and *SE*. Hence, the two different flood generating events both have significantly high occurrence in *W* and *SW* and significantly low occurrence in *NE, E* and *SE*. This would indicate that some LCCs are associated with high/low occurrence of both precipitation and water level events. However, currently high precipitation and water level events occur in different seasons and, therefore, concurrent events are rare.

Concurrent events showed a significantly high occurrence in LCC *W* and a significantly low occurrence in LCC *A* using a threshold of 20 events/year. It should be noted that the analysis of concurrent events was based on very few observations (in total 30 events over a time period of 23 years). Overall the results are in accordance with the assessment of significant occurrence for precipitation and water level events separately.

Relationships of water level events and combinations of LCCs ($LCC_{same\ day}$-$LCC_{previous\ day}$ pairs) the same day and the day before using 20 events per year showed that westerly directions (*W-W, W-NW*, and *SW-SW*) obtained significantly high occurrence. In addition, anti-cyclonic weather, if occurring during several days (*A-A*) or in combination with southerly circulation (*A-S*), showed significantly high occurrence.

With regards to assessing future occurrence of precipitation/water level events we found changes in both individual and concurrent frequencies between -1 and 19% of current occurrence rates. The differences between observed LCCs and LCCs calculated based on RCM output are larger than the modelled changes between present climate and the future climate of 2070-2100.

5.1 Acknowledgements

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6 References

Arnbjerg-Nielsen, K., 2012. Quantification of Climate Change effects on extreme precipitation used for high resolution hydraulic design. *Urban Water Journal,* 9(2), pp. 57-65. doi: 10.1080/1573062X.2011.630091.

Apel, H. Thieken, A.H., Merz B., Blöschl G. Flood risk assessment an associated uncertainty. *Natural Hazards and Earth System Science*, 2004, 4(2), pp. 295-308. doi:10.5194/nhess-4-295-2004.

van den Besselaar, E.J.M., A.M.G. Klein Tank and G. van der Schrier, 2010, Influence of circulation types on temperature extremes in Europe. *Theor. Appl. Climatol.*, 99 (3), 431-439. doi:10.1007/s00704-009-0153-6.

Betts, A. & Beljaars, A., 2003. *ECMWF ISLSCP-II near-surface datasets from ERA-40,* Berks: ECMWF.

Chen, D., 2000. A monthly circulation climatology for Sweden and its application to a winter temperature case study. *International Journal of Climatology,* 20, pp. 1067-1076.

Demuzere, M., Werner, M., van Lipzig, N. P. M. and Roeckner, E., 2009. An analysis of present and future ECHAM5 pressure fields using a classification of circulation patterns. *International Journal of Climatology*, 29, pp. 1796–1810. doi: 10.1002/joc.1821.

Fernández-González, S., del Rio, S., Castro, A., Penas, A., Fernández-Raga, M., Calvo, A., et al., 2012. Connection between NAO, weather types and precipitation in León, Spain (1948–2008). *International Journal of Climatology*. 32, 2181–2196. doi: 10.1002/ joc.2431.

Garavaglia, F. et al., 2010. Introducing a rainfall compound distribution model based on weather patterns sub-sampling. *Hydrology and Earth System Sciences,* 14, pp. 951-964. doi: 10.5194/hess-14-951-2010.

Gregersen, I., Madsen, H., Rosbjerg, D. & Arnbjerg-Nielsen, K., 2014. Long term variations of extreme rainfall in Denmark and southern Sweden. *Climate Dynamics. In Press.*

Grimalt M., Tomas M., Alomar G., Martin-Vide J., Moreno-Garcia M.C.: Determination of the Jenkinson and Collison's weather types for the western Mediterranean basin over the 1948-2009 period. *Temporal analysis. Atmósfera* 26(1), 75-94, 2013.

Hallegatte, S., Green, C., Nicholls, R., Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. *Nature climate change,* Volume 3, pp. 802-806. doi:10.1038/nclimate1979.

Huth, R., Beck, C., Philipp, A., Demuzere, M., Ustrnul, Z., Cahynová, M., Kyselý, J., Tveito, O.E., 2008. Classification of Atmospheric Circulation Patterns - Recent Advances and Application. *Annals of the New York Academy of Sciences,* 1146, pp. 105-152. doi: 10.1196/annals.1446.019.

Jacobeit, J., 2010. Classifications in climate research. *Physics and Chemistry of the Earth, Parts A/B/C,* 35 (9-12), pp. 411-421. doi:10.1016/j.pce.2009.11.010.

Jenkinson, A. & Collison, F., 1977. An initial climatology of gales in North Sea. *Synoptic Climatology Branch Memorandum No. 62,* Meteorological Office, Bracknell.

Johnson, R. A., Gupta, C.B., 2005. *Probability and Statistics for Engineering.* Pearson Education, Inc. 7th edition, John Wiley.

Jones, P., Hulme, M. & Briffa, K., 1993. A comparison of Lamb circulation types with an objective classification scheme. *International Journal of Climatology,* 13, pp. 655-663.

Jones, P., Harpham, C., Briffa, K.R., 2013. Lamb weather types derived from reanalysis products. *International Journal of Climatology*, 33, pp. 1129-1139. Doi: 10.1002/joc.3498, 2012.

Jones P.D., Osborn T.J., Harpham C. and Briffa K.R.: The Development of Lamb Weather types: from subjective analysis of weather charts to objective approaches using Reanalyses *Weather 69*: 128-132, DOI: 10.1002/wea.2255, 2014.

Kidson, J. W., 1994. The relation of New Zealand daily and monthly weather patterns to synoptic weather types. *International Journal of Climatology,* 14, pp. 723-737.

Lamb, H., 1950. Types and spell of weather around the year in the British Isles. *Quarterly Journal of the Royal Meteorological Society,* 76, pp. 393-438.

van der Linden, P. & Mitchell, J., 2009. *ENSEMBLES: Climate Change and its Impacts: Summary of Research from the ENSEMBLES Project.* Exeter: Met Office Hadley Centre.

Linderson, M.-L., 2001. Objective classification of atmospheric circulation over southern Scandinavia. *International Journal of Climatology,* 21, pp. 155-169. doi: 10.1002/joc.604.

Lorenzo M.N., Ramos A.M., Taboada J.J., Gimeno L., 2011. Changes in Present and Future Circulation Types Frequency in Northwest Iberian Peninsula. *PLoS ONE*, 6(1), e16201. doi:10.1371/journal.pone.0016201.

Longfield, S. & Macklin, M., 1999. The influence of recent environmental change in flooding and sediment fluxes in the Yorkshire Ouse basin. *Hydrological processes,* 13, pp. 1051-1066. doi: 10.1002/(SICI)1099-1085(199905)13:7<1051::AID-HYP789>3.0.CO;2-R.

Lupikasza, E., 2010. Relationships between occurrence of high precipitation and atmospheric circulation in Poland using different classifications of circulation types. *Physics and Chemistry of the Earth,* 35 (9-12), pp. 448-455. doi:10.1016/j.pce.2009.11.012.

MIKE by DHI (2013) EVA – Extreme Value Analysis – Technical Reference and Documentation. MIKE by DHI 2014.

Madsen, H., Steen Mikkelsen, P., Rosbjerg, D. & Harremoës, P., 2002. Regional estimation of rainfall intensity-duration-frequency curves using generalized least squares regression of partial duration series statistics. *Water Resources Research,* 38(11), pp. 1-11. doi: 10.1029/2001WR001125.

Mayes, J.C., 1991. Regional airflow patterns in the British Isles. *International Journal of Climatology,* 11(5), pp. 473-491. doi: 10.1002/joc.3370110502.

Pattison, I. & Lane, S. N., 2012. The relationship between Lamb weather types and long-term changes in flood frequency, river Eden, UK. *International Journal of Climatology,* 32 (12), pp. 1971-1989. doi: 10.1002/joc.2415.

Pedersen, A., Mikkelsen, P. & Arnbjerg-Nielsen, K., 2012. Climate change-induced impacts in urban flood risk influenced by concurrent hazards. *Journal of Flood Risk Management,* 5(3), pp. 203-214. doi: 10.1111/j.1753-318x.2012.01139.x.

Philipp, A. et al., 2010. Cost733cat - A database of weather and circulation type classifications. *Physics and Chemistry of the Earth,* 35(9-12), pp. 360-373. doi: doi:10.1016/j.pce.2009.12.010.

Post, P., Truija, V. & Tuulik, J., 2002. Circulation weather types and their influence on temperature and precipitation in Estonia. *Boreal Environment research,* 7, pp. 281-289.

Ramos A.M., Cortesi N. and Trigo R.M.: Circulation weather types and spatial variability of daily precipitation in the Iberian Peninsula, *Frontiers in Earth Sciences*, DOI: 10.3389/feart.2014.00025, 2014.

Schiemann, R. & Frei, C., 2009. How to quantify the resolution of surface climate by circulation types: An example for Alpine region. *Physics and Chemistry of the Earth,* 35, pp. 403-410. doi: 10.1016/j.pce.2009.09.005.

Stehlik, J. & Bárdossy, A., 2002. Multivariate stochastic downscaling model for generating daily precipitation series based on atmospheric circulation. *Journal of Hydrology,* 26(1-2), pp. 120-141. doi:10.1016/S0022-1694(01)00529-7.

Sunyer, M., Gregersen, I., Rosbjerg, D., Madsen, H., Luchner, J., Arnbjerg-Nielsen, K., 2015. Comparison of different statistical downscaling methods to estimate changes in hourly extreme precipitation using RCM projections from ENSEMBLES. *International Journal of Climatology, 35, 2528–2539.* doi: 10.1002/joc.4138.

Svensson, C., Jakob, D. & Reed, D.W., 2002. Diurnal characteristics of heavy precipitation according to weather type at an upland site in Scotland. *International Journal of Climatology,* 22, pp. 569-585. doi: 10.1002/joc.672.

Swiss Reinsurance Company Ltd (SwissRe), 2012. *Flood – an underestimated risk: Inspect, inform, insure.* Zurich: Swiss Re Logistics Media Production.

Trigo, R. M. & DaCamara, C. C., 2000. Circulation weather types and their influence on the precipitation regime in Portugal. *International Journal of Climatology,* 20 (13), pp. 1559-1581. doi: 10.1002/1097-0088(20001115)20:13<1559::AID-JOC555>3.0.CO;2-5.

Wetterhall, F., Pappenberger, F., He, Y., Freer, J., and Cloke, H. L., 2012. Conditioning model output statistics of regional climate model precipitation on circulation patterns, *Nonlin. Processes Geophys*., 19, pp. 623-633, doi:10.5194/npg-19-623-2012.

Willems, P., 2013. Multidecadal oscillatory behaviour of rainfall extremes in Europe. *Climatic Change,* 120 (4), pp. 931-944. doi: 10.1007/s10584-013-0837-x.

Zevenbergen, C., Veerbeek, W., Gersonius, B. & van Herk, S., 2008. Challenges in urban flood management: travelling across spatial and temporal scales. *Flood Risk Management,* 1, pp. 81-88. doi: 10.1111/j.1753-318X.2008.00010.x.

Zhou, Q., Mikkelsen, P., Halsnæs, K. & Arnbjerg-Nielsen, K., 2012. Framework for Economic Pluvial Flood Risk Assessment considering Climate Change Effects and Adaptation Benefits. *Journal of Hydrology,* 414-415, pp. 539-549. doi: doi:10.1016/j.jhydrol.2011.11.031.

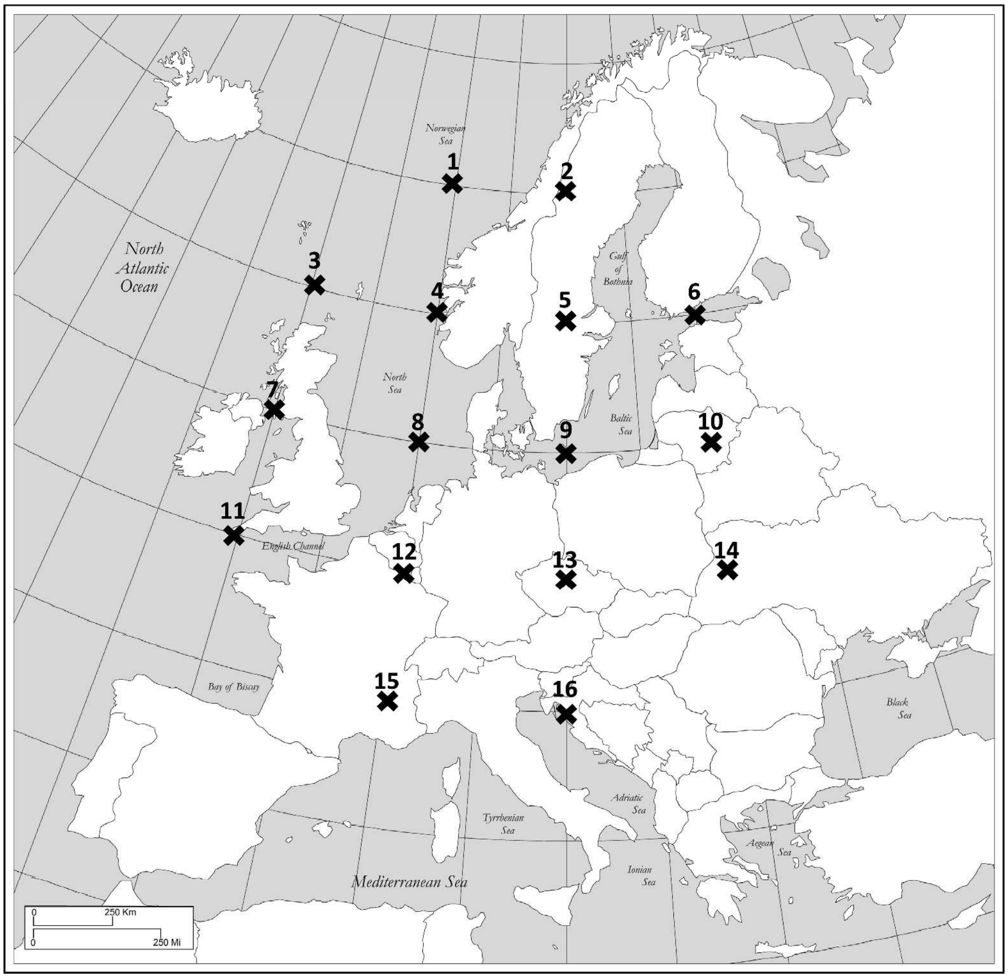


Figure 1 – Grid points for which mean sea level pressure was extracted for the calculation of LCTs. Centre line is located at latitude 55N.
494x479mm (300 x 300 DPI)

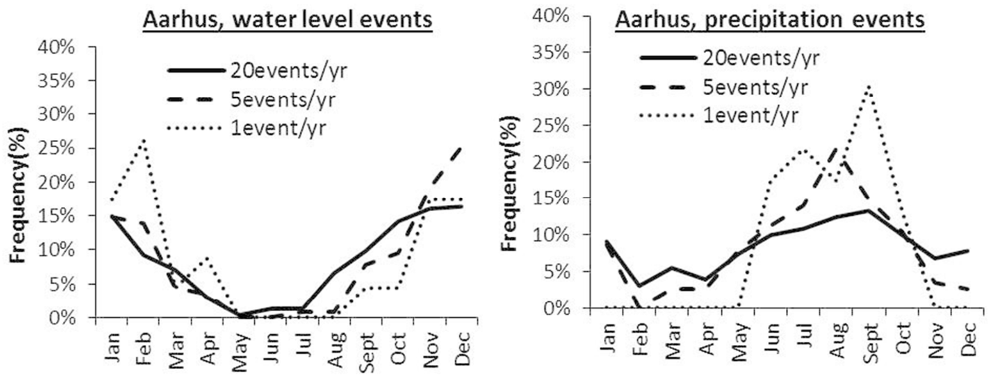


Figure 2 – Monthly frequency of extracted precipitation events (right) and water level events (left) for the thresholds 20, 5 and 1 events/year.
80x32mm (300 x 300 DPI)

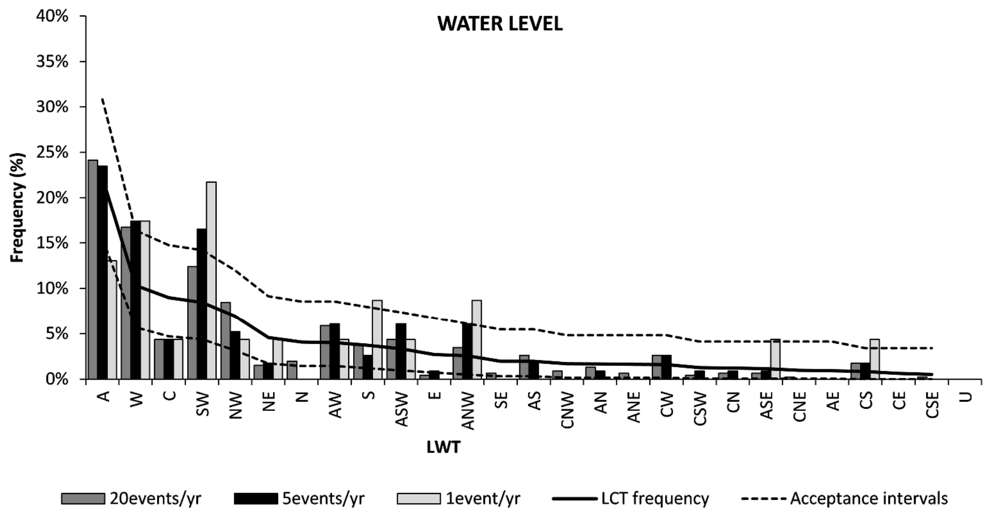


Figure 4 – Bars represent the occurrence frequency of extreme water level events in each LCT for thresholds 20, 5 and 1 events/year. Full line represents total occurrence frequency of LCTs. Acceptance intervals for the threshold 5 events/year are represented by the dashed lines. occurrence frequency of LCTs. Acceptance intervals for the threshold 5 events/year are represented by the dashed lines.
413x222mm (300 x 300 DPI)

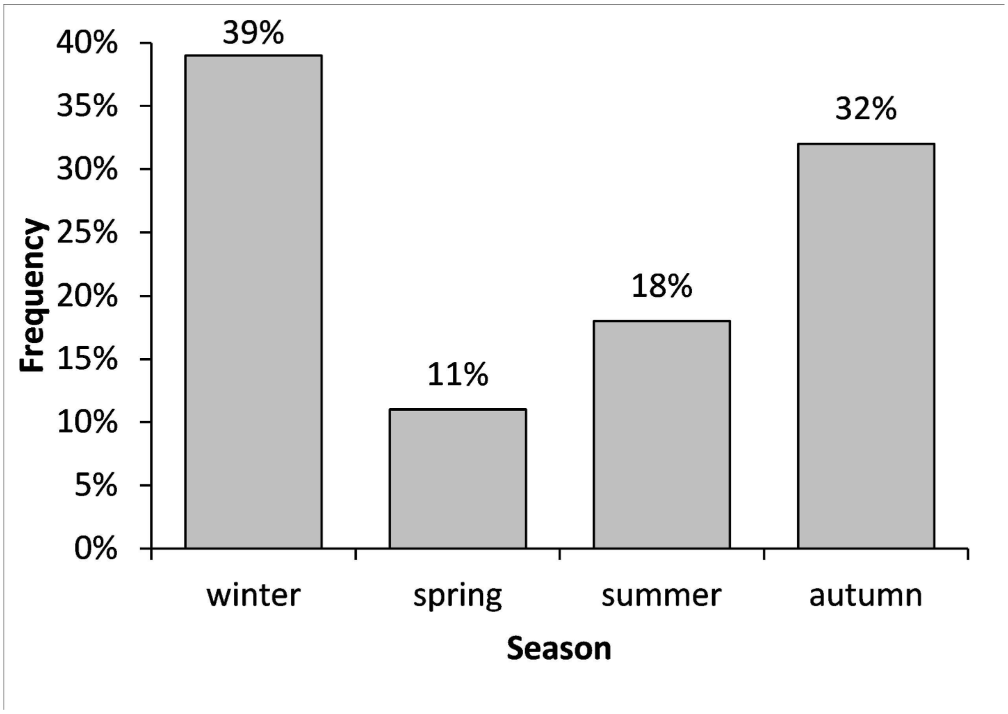


Figure 5 – Seasonal frequency of concurrent events.
215x152mm (300 x 300 DPI)

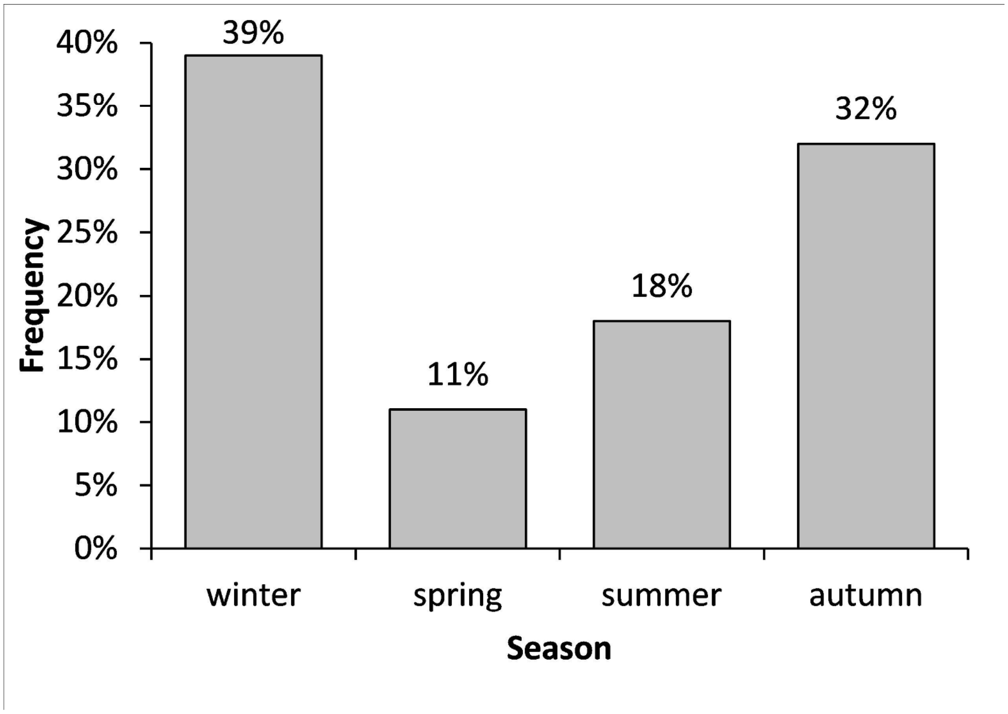


Figure 5 – Seasonal frequency of concurrent events.
215x152mm (300 x 300 DPI)

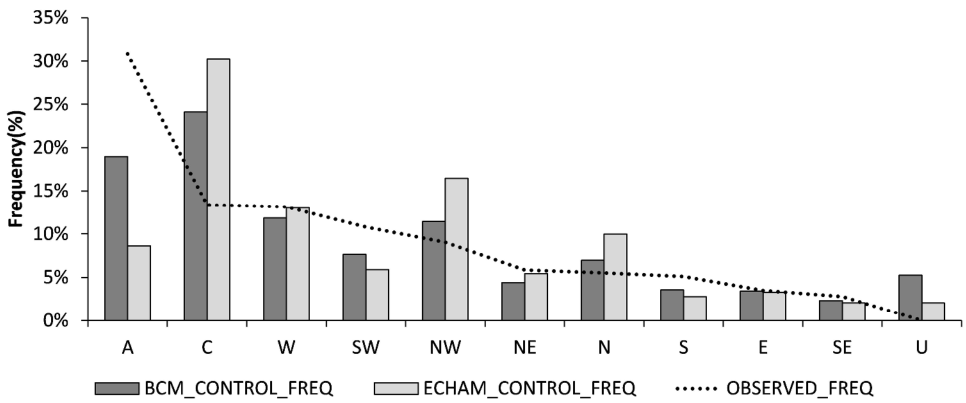
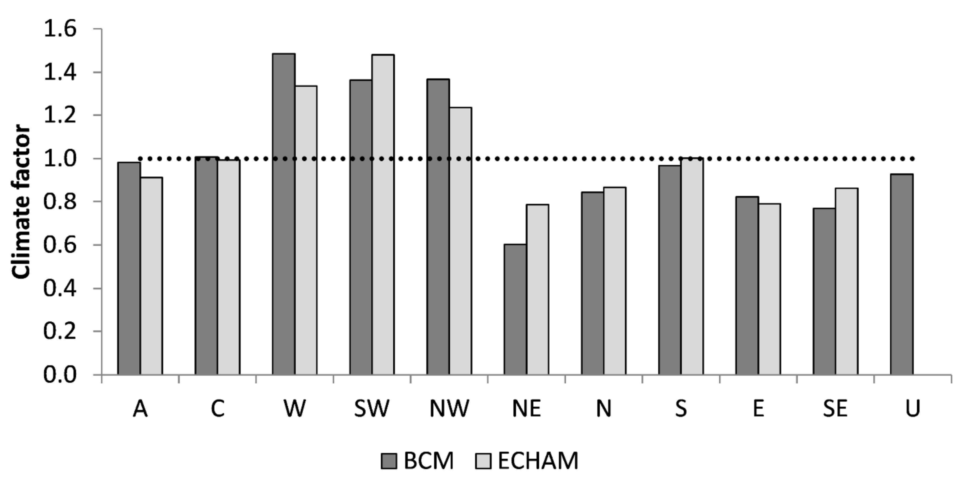


Figure 7 – Frequency of LCCs for RCMs BCM/HIRHAM (BCM_CONTROL_FREQ) and ECHAM/HIRHAM (ECHAM_CONTROL_FREQ) for the control period and the observed frequency (OBSERVED_FREQ) of LCCs (dashed line).
405x170mm (300 x 300 DPI)



Climate factors (CFs) for ECHAM/HIRHAM and BCM/HIRHAM.
658x327mm (144 x 144 DPI)

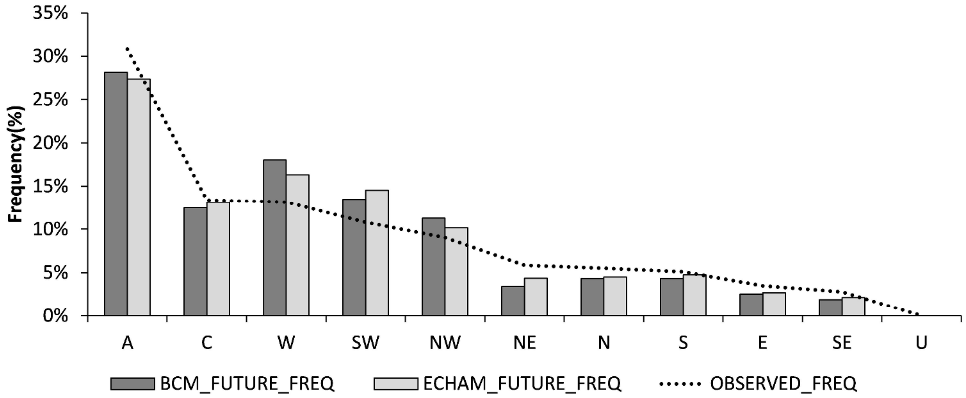


Figure 9 – Projected future occurrence frequencies for RCMs BCM (BCM_FUTURE_FREQ) and ECHAM (ECHAM_FUTURE_FREQ), and observed frequencies (OBSERVED_FREQ) for LCCs.
405x170mm (300 x 300 DPI)

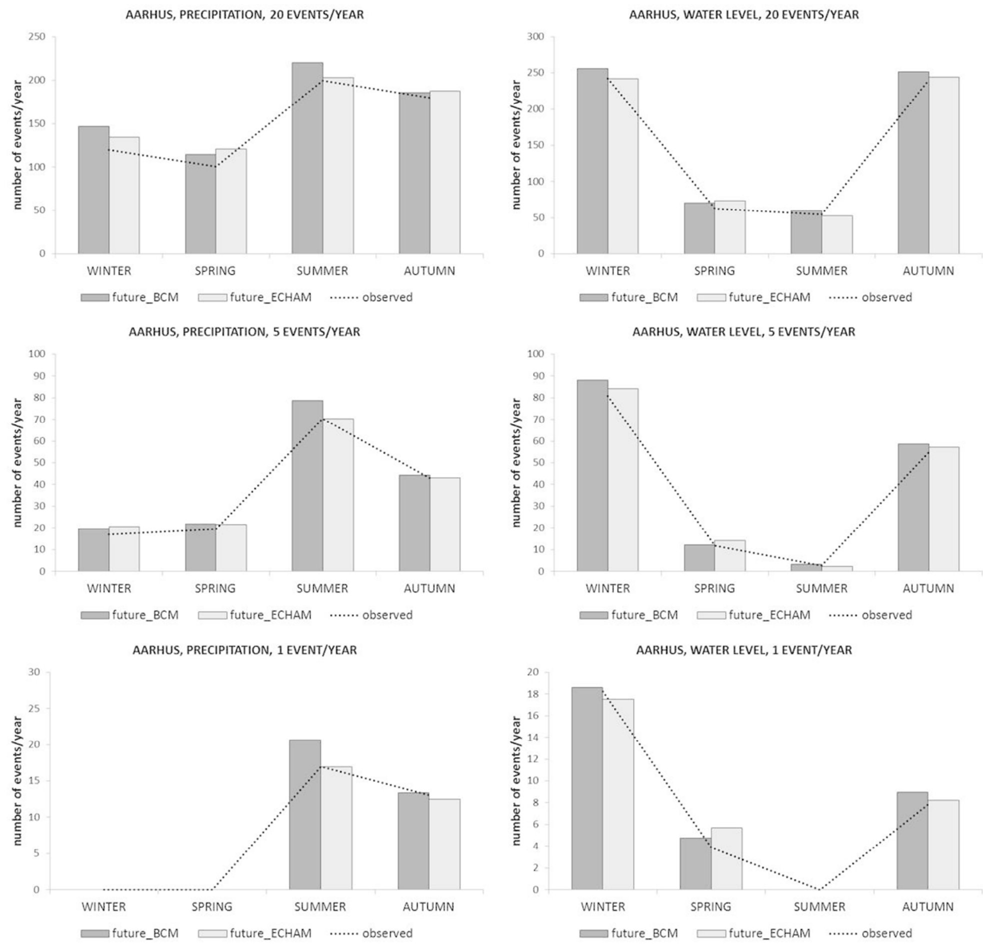


Figure 10 - Seasonal occurrence of precipitation (left) and water level (right) events. Figures present the observed occurrence (line) and the future occurrence calculated using RCMs BCM/HIRHAM and ECHAM/HIRHAM. Results are presented for the thresholds 20, 5 and 1 events/year.
106x102mm (300 x 300 DPI)

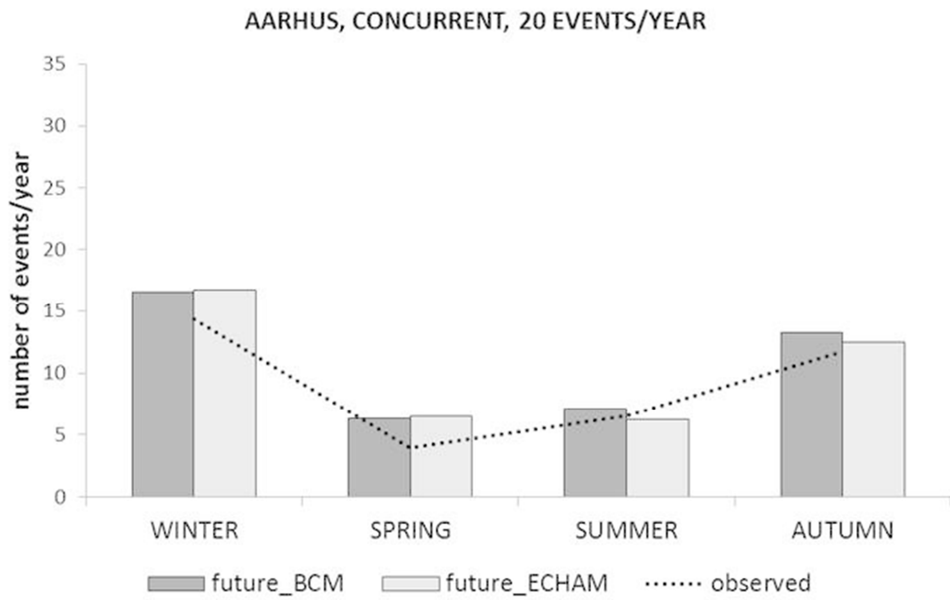


Figure 11 – Seasonal occurrence of concurrent events. Figures present the observed occurrence (line) and the future occurrence calculated using RCMs BCM/HIRHAM and ECHAM/HIRHAM.
60x38mm (300 x 300 DPI)

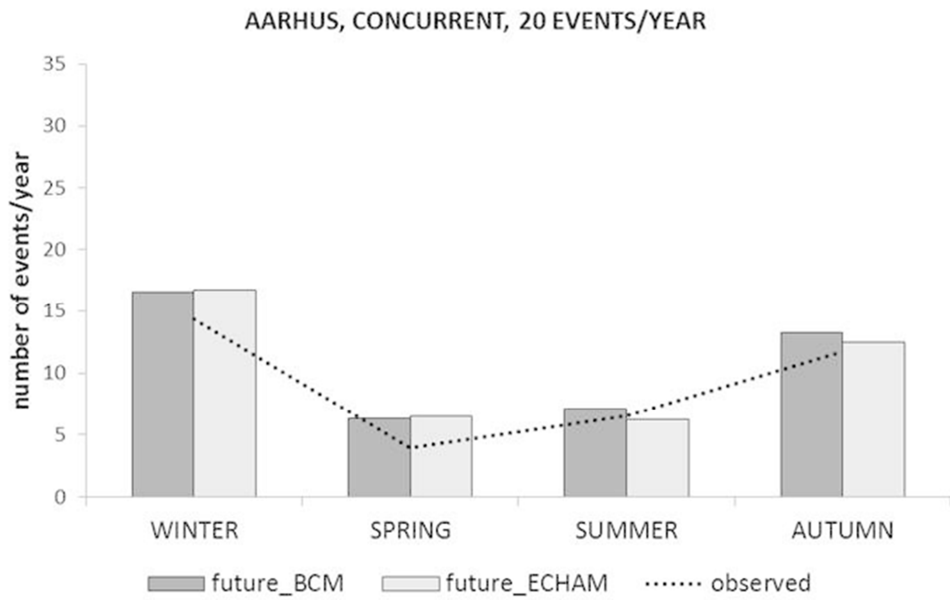


Figure 11 – Seasonal occurrence of concurrent events. Figures present the observed occurrence (line) and the future occurrence calculated using RCMs BCM/HIRHAM and ECHAM/HIRHAM.
60x38mm (300 x 300 DPI)

Table 1 – Thresholds corresponding to average annual amount of exceedances of 20, 5 and 1 events/years for water level and precipitation extremes.

Variable	Unit	20 events/year	5 events/year	1 event/year
Water level	m	0.31	0.57	0.83
Precipitation	mm/3h	4.20	8.80	16.00

Table 2 – LCT/LCC occurrence frequency (f_i) for the time period 1979-2001 over Denmark (grey represents LCCs) for thresholds 20, 5 and 1 events/year.

LCT/LCC		f_i (LCT)	f_i (LCC)
A	Anticyclonic	22.2%	30.8%
W	Westerly	10.3%	13.1%
C	Cyclonic	9.0%	13.4%
SW	South-westerly	8.5%	10.8%
NW	North-westerly	6.9%	9.1%
NE	North-easterly	4.6%	5.8%
N	Northerly	4.1%	5.5%
AW	anticyclonic westerly	4.0%	
S	Southerly	3.7%	5.1%
ASW	anticyclonic south-westerly	3.3%	
E	Easterly	2.7%	3.5%
ANW	anticyclonic north-westerly	2.6%	
SE	South-easterly	2.0%	2.8%
AS	anticyclonic southerly	2.0%	
CNW	cyclonic north-westerly	1.7%	
AN	anticyclonic northerly	1.7%	
ANE	anticyclonic north-easterly	1.6%	
CW	cyclonic westerly	1.6%	
CSW	cyclonic south-westerly	1.3%	
CN	cyclonic north-easterly	1.2%	
ASE	anticyclonic south-easterly	1.1%	
CNE	cyclonic north-easterly	1.0%	
AE	anticyclonic easterly	0.9%	
CS	cyclonic southerly	0.8%	
CE	cyclonic easterly	0.6%	
CSE	cyclonic south-easterly	0.5%	
U	Unclassified	0.0%	

Table 3. Overview of which LCTs/LCCs have a significantly LOW/HIGH occurrence of precipitation events for α=0.2 Significantly low occurrence is described in the tables as LOW and dark grey represents LCTs/LCCs with low, but not significant, occurrence. Similarly, significantly high occurrence is described as HIGH and high, but not significant, is presented with light grey. LCTs/LCCs with a low occurrence, but for which the lower acceptance level could not be calculated due to a low expected number of events, are presented as white. Finally, black describes which CTs are not included into the LCC classification.

	20 events/year		5events/year		1event/year	
	LCT	LCC	LCT	LCC	LCT	LCC
A	LOW	LOW	LOW	LOW	LOW	
W	HIGH	HIGH				
C	HIGH	HIGH	HIGH	HIGH		
SW	HIGH	HIGH	HIGH	HIGH		
NW	HIGH	HIGH				
NE	LOW	LOW		LOW	LOW	LOW
N	LOW	LOW				
AW						
S					LOW	LOW
ASW						
E	LOW	LOW		LOW	LOW	LOW
ANW					LOW	
SE	LOW	LOW	LOW	LOW		LOW
AS						
CNW						
AN	LOW					
ANE	LOW		LOW			
CW	HIGH					
CSW					HIGH	
CN						
ASE	LOW		LOW			
CNE			LOW			
AE	LOW		LOW			
CS						
CE			LOW			
CSE			LOW			

Table 4. Overview of which LCTs/LCCs have a significant low/high occurrence of water level events for α=0.2 Significantly low occurrence is described in the tables as LOW and dark grey represents LCTs/LCCs with low, but not significant, occurrence. Similarly, significantly high occurrence is described as HIGH and high, but not significant, is presented with light grey. LCTs/LCCs with a low occurrence, but for which the lower acceptance level could not be calculated due to a low expected number of events, are presented as white. Finally, black describes which CTs are not included into the LCC classification.

	20 events/year		5 events/year		1 event/year	
	LCT	LCC	LCT	LCC	LCT	LCC
A						
W	HIGH	HIGH	HIGH	HIGH		
C	LOW	LOW	LOW			
SW	HIGH	HIGH	HIGH	HIGH		
NW						
NE	LOW	LOW		LOW		
N	LOW		LOW	LOW	LOW	LOW
AW	HIGH					
S						
ASW						
E	LOW	LOW		LOW	LOW	LOW
ANW						
SE	LOW	LOW	LOW	LOW		
AS						
CNW			LOW			
AN						
ANE	LOW		LOW			
CW						
CSW	LOW					
CN						
ASE						
CNE	LOW		LOW			
AE	LOW		LOW			
CS						
CE	LOW		LOW			
CSE			LOW			

Table 5. Overview of which combination of LCCs the same day and the day before the water level events has a significantly lower/higher occurrence for α=0.2 and 20 events/year. Significantly low occurrence is described in the tables as LOW and dark grey represents LCTs/LCCs with low, but not significant, occurrence. Similarly, significantly high occurrence is described as HIGH and high, but not significant, is presented with light grey.

Same day

Day before	A	C	W	SW	NW	NE	N	S	E	SE
A	HIGH	LOW		LOW					LOW	
C	LOW									
W			HIGH			LOW		LOW		
SW				HIGH		LOW				
NW	LOW		HIGH			LOW		LOW		LOW
NE			LOW	LOW						
N	LOW			LOW						
S	HIGH		LOW		LOW	LOW				
E	LOW		LOW							
SE			LOW							

Table 6 - Overview of which combination of LCCs the same day and the day before the water level events has a significantly lower/higher occurrence for α=0.2 and 5 events/year. Significantly low occurrence is described in the tables as LOW and dark grey represents LCTs/LCCs with low, but not significant, occurrence. Similarly, significantly high occurrence is described as HIGH and high, but not significant, is presented with light grey.

Same day (columns); Day before (rows)

Day before	A	C	W	SW	NW	NE	N	S	E	SE
A		LOW		LOW						
C										
W			HIGH					LOW		
SW										
NW	LOW			LOW				LOW		
NE										
N	LOW									
S		LOW	LOW							
E										
SE										

Table 7. Change (in percent) in the number of water level, precipitation and concurrent events between current and future time period calculated as (λ_{fut} - λ)/ λ , where λ is the current number of extreme events/year (i.e. thresholds 20, 5 or 1 events/year) and λ_{fut} is the calculated future number of extreme events/year using change in LCC frequency.

	BCM/HIRHAM			ECHAM/HIRHAM		
Events	**20 events/yr**	**5 events/yr**	**1 event/yr**	**20 events/yr**	**5 events/yr**	**1 event/yr**
Water level	6.5%	8.1%	7.8%	2.1%	5.2%	4.8%
Precipitation	11.2%	9.7%	13.2%	7.6%	3.6%	-1.0%
Concurrent	18.5%	-	-	14.8%	-	-